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COMPARATIVE ANALYSIS OF MECHANICAL RELIABILITY DETERMINATION TE--ETC(U)
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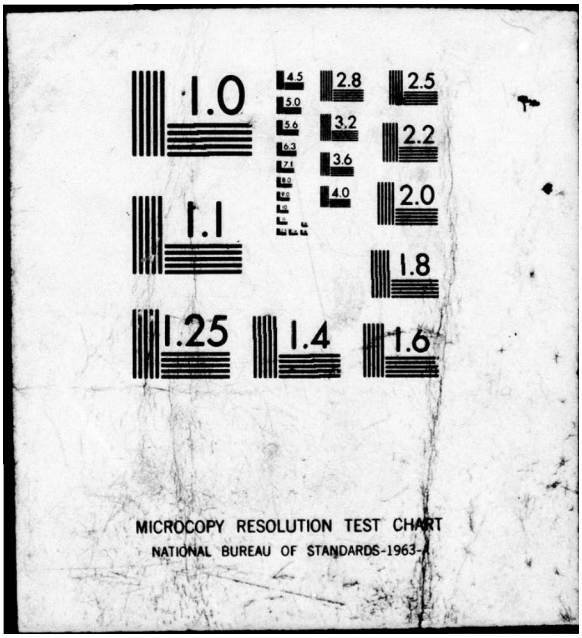
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COMPARATIVE ANALYSIS OF MECHANICAL RELIABILITY DETERMINATION TECHNIQUES

June 1976

Prepared for

Naval Weapons Engineering Support Activity

Building 200, Washington Navy Yard

Washington, D.C. 20374

Under Contract N68335 - 76 - C - 2253 - new

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (14) LTU-2253-1	2. GOVT ACCESSION NO. / 3. RECIPIENT'S CATALOG NUMBER (9)
4. TITLE (and Subtitle) (6) Comparative Analysis of Mechanical Reliability Determination Techniques	5. TYPE OF REPORT & PERIOD COVERED (13) Research Report. November 1974-June 1976
(10)	6. PERFORMING ORG. REPORT NUMBER LTU-1
7. AUTHOR(s) Dr. Jack Canterbury, Dr. James D. Lowther	8. CONTRACT OR GRANT NUMBER(s) (15) N68335-76-C-2253
9. PERFORMING ORGANIZATION NAME AND ADDRESS Louisiana Tech University Ruston, LA 71270	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62760N/53-532/403
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Weapons Engineering Support Activity (ESA-116) Wash. Navy Yard, Washington, DC 20374	12. REPORT DATE (11) 30 June 1976 / 13. NUMBER OF PAGES 44
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Same as 11. (12) 49p.	15. SECURITY CLASS. (of this report) Unclassified / 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release; distribution unlimited.

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Reliability Determination	Mechanical Reliability
Reliability Testing	Reliability Data Management
Regression Analysis	Figures of Merit
Mechanical Equipment Classification	Failure Modes and Mechanisms

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report identifies, evaluates and compares the techniques presently available for mechanical reliability prediction. Techniques are classified in the following categories: design procedures incorporating reliability, techniques for predicting reliability, techniques for obtaining reliability data, and techniques for data analysis.

A general approach for developing mechanical reliability prediction capability is outlined and research needed to further develop the prediction capability is specified.

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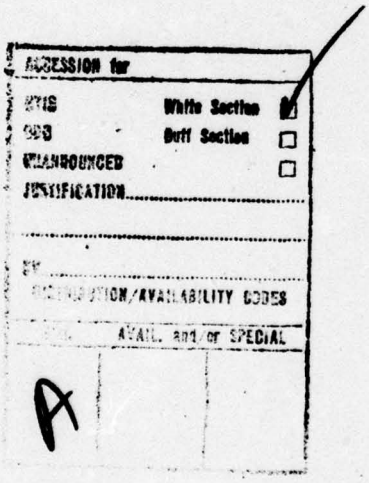

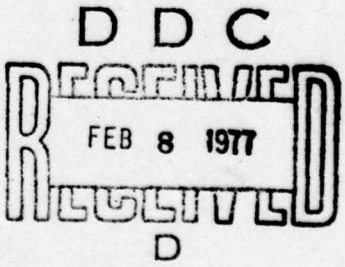

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INTRODUCTION

This report is the result of efforts by investigators at Louisiana Tech University to identify, evaluate, and compare available mechanical reliability determination techniques, recommend an approach for combining the best techniques into a unified theory for mechanical reliability prediction, and to identify further research needed to develop a unified theory.

Many good ideas, concepts, and techniques have been produced and developed in the field of reliability during the last 20 years and a fairly large volume of information exists from a broad range of sources and covering a wide range of topics from different viewpoints. This report is not intended to be a treatise on reliability or even mechanical reliability in general. The report is prepared for a reader who has a good basic understanding of reliability concepts, knows generally why and how mechanical reliability is special and different from electronic component reliability, and knows that a need exists for organizing existing information as well as a need for still more new ideas.

Although the investigation was related to techniques used in mechanical reliability, the guiding factor was the need for better abilities to design for better mechanical reliability. That is, the theme is: Mechanical reliability as it relates to design. The fact that mechanical reliability also depends on the manufacture, shipping, storage, installation, use, etc. is not completely ignored, but these are important in this analysis only to the extent that design must take them into consideration. On the other hand this investigation is not to be considered as a design procedure investigation. Design is

considered only to the extent that mechanical reliability is involved. Cost, maintainability and other factors closely related to reliability are not considered.

Before getting into the more important parts of the report a few general statements are in order. These statements should help to establish the basis and overall perspective from which the authors have developed the ideas for the remainder of the report.

The ability to analyze and predict mechanical reliability has improved in recent years due to more and better knowledge of physics of failure, data analysis, and other areas of study. At the same time the demands for more ability have increased considerably due mainly to more complex and more sophisticated designs. This combination of facts makes the need for organization of techniques into a unified theory more important than ever. So far no known single technique or approach is recognized as qutstanding above all others for all cases. The most feasible approach to prediction of mechanical reliability is outlined in the section entitled RECOMMENDED APPROACH.

One way of illustrating the growing need for a unified theory that relates to design is to look at the viewpoints of three different persons: the reliability analyst, the designer, and the manager. From the viewpoint of the reliability analyst, reliability analysis may have any of several purposes. These include generating generic failure rates, maintenance cost reduction, knowledge for spare part stocks, and others as well as for better design. The designer sees the demands for reliability expertise as too big a price for implementing the complex procedures of the reliability analyst. The manager, however, wants a compromise that results in some simplified useable procedure for the designer to use that will result in more reliable designs and

specifically designs with predictable reliabilities. The compromise that meets this requirement might be considered as the primary goal of this investigation and the recommended further work needed discussed later.

When and if suitable procedures are developed to fit the best techniques to the problem at hand, a serious problem in mechanical reliability analysis and prediction still exists--data requirements. Mainly the amount of data necessary is the problem, but the procedures used to generate the data and make them of maximum use are also important. Ideas for reducing this problem are discussed in the later sections of this report relating to recommended approaches and further work needed.

Terminology is sometimes confusing in the field of mechanical reliability. One of the main problems is the variety of terms used to describe essentially the same thing--such as, figure of merit or dependent variable. Other terms have vague meanings which depend upon the context in which used, or simply mean different things to different people. Such a term is "probabilistic design". Probabilistic design, probabilistic modeling, and statistical modeling are terms used when referring to mathematical procedures when statistical analyses are used. Mathematical modeling is a much broader term although one commonly accepted meaning of mathematical modeling is the mathematical expression of the reliability of a system in terms of the reliabilities of the individual components of the system. Design safety factors are not used in probabilistic modeling but usually are used otherwise. Any unified theory should be constructed around well defined and well understood terms insofar as possible.

A final few words by way of introduction concern the topics of (1) figures of merit, (2) failure modes, and (3) mechanical hardware classification. Each of these is an integral part of any approach to a unified theory on mechanical reliability prediction. Also each topic is involved enough to deserve a specific effort to organize the available material to best fit it into a unified theory. This is discussed in more detail in the section entitled FURTHER WORK NEEDED.

EXISTING MECHANICAL RELIABILITY TECHNIQUES

Many techniques exist for a number of different purposes in mechanical reliability analysis and prediction. Many different methods could be used for classifying or evaluating these techniques. One might even consider rating the techniques on some quality scale for a number of desirable characteristics such as adaptability, accurateness, complexity, etc. After careful consideration of a number of possibilities, it was decided that a grouping would be made based on the primary purpose of the technique and a discussion and comparison be made within that grouping. Also, keeping in mind that better design is the guiding factor for the whole investigation, it seemed proper to begin the discussion with mechanical design procedures incorporating reliability. Within this topic some techniques that relate directly to different philosophies of design are discussed. After that techniques for predicting mechanical reliability are discussed; then techniques for obtaining data; then techniques for data analysis; and finally other techniques for special purposes or techniques that do not fit specifically into other groupings.

Two important points should be emphasized before a full discussion of techniques is begun. The first point is that many techniques commonly referred to as mechanical reliability prediction techniques are in reality techniques for obtaining data (such as "accelerated testing") or analyzing data ("regression analysis") and cannot by themselves be used to predict reliability. This is the main reason for classifying techniques by purpose. The second point is that this section is for the purpose of classifying, identifying, and, to a limited degree, comparing and evaluating the techniques. The evaluation

and comparison is abbreviated considerably, but methods with considerable merit are discussed more fully in the sections entitled RECOMMENDED APPROACH and FURTHER WORK NEEDED.

Mechanical Design Procedures Incorporating Reliability

Reliability is a design parameter in all design of mechanical components, either explicitly as a part of the design procedure, or implicitly in the case where reliability is not considered quantitatively in the design procedure, although the design will obviously possess a certain reliability. This report is concerned with reliability as an explicit parameter in the design procedure.

The incorporation of reliability into the mechanical design process can be accomplished through one of three approaches or a combination of these approaches:

1. Gross Overdesign
2. Reliability Growth
3. Reliability Prediction

Gross Overdesign. In the gross overdesign approach, no detailed predictions of reliability are made, but design procedures are used which in general can be expected to produce a design of high reliability. Such procedures include the use of redundancy, very large factors of safety (equivalent to "derating" the equipment, or operating at a partial load), simplicity, and the utilization of standardized components of known reliability (1).* Such a design procedure has the advantage of being fast, simple and low in design cost. Simplicity of design and the use of standardized parts are generally accepted as being desirable

*Numbers in parentheses refer to entry in the LIST OF REFERENCES.

design philosophies; however, the use of redundancy and large safety factors generally exacts a heavy penalty in terms of weight and cost of manufacture of the product. One of the other approaches can be expected to produce a design that will meet given reliability requirements and be lighter in weight and lower in cost. In addition, reliability of the product cannot be determined at design time when the gross overdesign approach is used. Furthermore, if the design departs radically from previous designs and existing technology, gross overdesign may not produce a high reliability design at all.

Reliability Growth. The reliability growth (2, 3) approach is sometimes referred to as the "development" stage of a design. In this approach, a device is initially designed without the use of extremely large safety factors and extensive redundancy and without predicting the reliability of the device. Reliability is determined and weak spots identified by testing of prototypes or first production models. Parts showing high failure rates in the tests are redesigned and the new design is tested. This iterative procedure is repeated until failure rates have been reduced to an acceptable level or until the reliability approaches a limiting value inherent in the basic design. The reliability growth approach produces a design for which reliability has been determined experimentally and one that is expected to be lighter in weight and cheaper to manufacture than a design based on the gross overdesign approach. The development period of iterative testing and redesign, however, requires a sizeable investment in time and money.

It should be noted that some elements of a reliability growth design may be overdesigned. The iterative testing and redesign procedure detects inadequacies in design only. Another important point concerning

the reliability growth approach is the fact that reliability growth does not predict reliability a priori. The reliability of the design is determined by testing during each iteration of the reliability growth process. After a few iterations, the trend of reliability vs. number of iterations completed can be established and the improvement in reliability for the next iteration can be estimated. The testing process does produce reliability data on a particular design which might possibly be used for another design project, but this information is incidental to the main purpose of the testing process.

Reliability Prediction. The reliability prediction method incorporates reliability parameters explicitly in the design process. A detailed knowledge of the reliability of mechanical devices is required. Here methods for prediction of the reliability of components and systems are required for use in the design. This approach produces a design meeting reliability specifications with a minimum of overdesign. This approach, therefore, should produce a design of minimum weight and cost of manufacture. This approach avoids the cost of iteratively redesigning and testing that is inherent in the reliability growth approach. The analytical design procedure for this method, however, will be more extensive and costly. Unfortunately, this method can only be applied to the simplest of designs at the present time because the ability to predict reliability is very limited at present.

The design of most complex systems is a combination of all three of the above approaches. A design using the reliability prediction method must ultimately be proven either by the testing of a prototype or through use of the first production models. If reliability specifications are not met, then some redesign will be necessary and the design procedure then becomes one of reliability growth. It can be seen that

there are an infinite number of variations of design procedure incorporating the three methods. For a given system, one of the three design approaches, or some combination, represents the most economical design.

As mentioned previously, the reliability prediction approach is possible only for very simple designs at present because the ability to predict reliability in terms of design parameters is very limited. The following section reviews the techniques presently available for predicting reliability of mechanical devices.

Techniques for Predicting Mechanical Reliability

Techniques for predicting mechanical reliability can be divided into two categories: those which utilize the single component concept and those which utilize the system concept. The single component concept deals with a single mechanical component or an assembly of components in terms of the reliability of the component or assembly as a whole. The reliabilities of individual components in an assembly are not used to predict the reliability of the assembly. For example, under the single component concept, the reliability of a turbine is predicted without the need for a knowledge of the reliability of the parts that make up the turbine (shafts, blades, bearings, seals, etc.) and without the need for a method of combining the reliability of the parts in order to predict the reliability of the turbine.

If the system concept is used, reliability may be predicted empirically by treating the system as a component or the reliability of an assembly of components may be predicted from the reliabilities of the components of the assembly. In the latter case, the ability to predict the reliability of each component is required. In addition, some method of combining the reliabilities of the components in order to predict the

reliability of the assembly is required. Under the system concept, the reliability of a turbine would be predicted using the reliabilities of the components (shaft, bearings, blades, etc.).

It is apparent that any assembly of two or more parts can be considered either as a single component or as a system for the purpose of predicting reliability. "Single components" and "systems" will vary in size and complexity. A hydraulic valve, the complete hydraulic system of an aircraft or even an entire aircraft can each be treated as either a single component or as a system for the purpose of predicting reliability. Both concepts are necessary in mechanical design.

The prediction of reliability, then, requires the ability to predict the reliability of what we have called a single component and the ability to predict the reliability of an assembly based on the reliabilities of the component parts.

Single component reliability prediction. Predictions of the reliability of a single component may be either theoretically or empirically based. The theoretical approach requires a detailed knowledge of failure mechanisms and the ability to construct a mathematical model representing expected loads, material strength, wear characteristics, etc. with which reliability can be predicted. Application of the theoretical approach is limited due to the fact that mathematical models can be developed only in relatively simple cases and extensive test programs are required to obtain supporting data.

By contrast, empirical reliability prediction does not require the construction of a mathematical model; however, all the pertinent parameters (independent variables) on which reliability depends must be identified. Once the pertinent variables are identified, experimental data (either laboratory-type or field-type) is obtained over the range of interest of

each of the independent variables. Since the number of independent variables on which reliability depends can be great, even for a mechanical component that is quite simple, the number of data points required is quite large.

Once the data is obtained, regression analysis can be employed to fit an equation for reliability vs. the independent variables to the data. This equation or correlation can then be used to predict reliability for the component on which the experimental data has been obtained.

1. Theoretical approach. The most widely used theoretical prediction method is referred to as the stress-strength interference technique. Work in this area has been effectively summarized by Mittenbergs (4).

For a mechanical component subject to a certain load, the mathematical model for the load is a statistical distribution of the stress (probability density function vs. stress) the part is subjected to under design operating conditions. The mathematical model for the strength of the component is a statistical distribution (probability density function vs. strength) of strengths a particular part may have due to variation in the materials, production processes, dimensions, etc. If the two distributions overlap then failure can occur (stress exceeds strength) and the probability of failure can be predicted from the probability density functions of stress and strength.

There are major problems associated with prediction of reliability using the stress-strain interference technique:

(1) The probability density functions for stress and strength must be known. The statistical distribution of loads and environmental conditions to which a mechanical device will be subjected are not usually known during the design stage. Simple, relatively inexact mathematical models must be used.

Statistical information on the material strength is scarce and scattered and an assumed statistical distribution must often be used.

(2) If the effects of wear, fatigue, corrosion, aging, etc. are to be accounted for, the probability density functions for stress and strength for a "new" device are not enough. The distribution must be known as a function of time over the expected life of the device. Statistical information on the variation of material properties with time is almost non-existent. It should be noted that stress distribution functions may also change with time due to wear and other factors. Although some work has been directed toward SST (stress-strength-time) theory (5), the work has been based on assumed distribution functions due to the lack of experimentally verified functions and the desire for mathematically tractable functions.

(3) Available statistical data on material properties are almost always taken from small samples, due to the cost and time involved in obtaining test data. Strength distributions based on small sizes are not exact at all in the low strength portion of the curve, even though the central portion of the curve may be reasonably exact.

Unfortunately, for the design of a mechanical device of high reliability, the low strength "tail" of the curve is the most important part since this is the region of overlap with the stress distribution curve. The fact that a good mathematical model describing the low-strength portion of the material property distribution curve cannot be obtained without using

large sample sizes makes the problem of data acquisition the most serious limitation of the stress-strength interference technique. It should be noted that the necessity of determining the strength distribution as a function of time (and, therefore, wear, aging, environmental conditions, etc.) compounds the data problem.

Work directed toward developing strength and stress distributions as a function of time so as to include the effects of fatigue, wear, aging, etc., has been called the physics of failure approach. In this approach mathematical models are developed based on the theories of materials science and stress analysis, often on a microscopic scale (6). Although the physics of failure approach has the advantage of providing insight into the basic nature of fatigue, wear, creep, corrosion, etc., the mathematical models will probably continue to be restricted to simple, single-part cases, and therefore will not be able to provide the information necessary for mathematical devices incorporating reliability.

A theoretical model that has been widely used to predict electronic reliability is the exponential distribution for reliability as a function of time. The exponential distribution is based on a failure rate that is constant in time. A constant failure rate is the result of purely random chance failures. Since mechanical devices subject to wear, fatigue etc. exhibit a failure rate that increases with time, the exponential distribution is not an acceptable mathematical model for the reliability of mechanical devices.

2. Empirical approach. The two basic requirements for utilization of the empirical approach for reliability prediction of a mechanical component are: (1) that all the independent variables affecting reliability be identified and (2) that experimental data on the reliability of the

component can be obtained while the pertinent independent variables are varied over the range of interest of each. For most mechanical components, the number of pertinent independent variables and the range of variables to be covered, together with the requirement for statistically significant sample sizes makes the amount of data required quite large. Once experimental data have been obtained, regression analysis can be employed to fit an equation for reliability as a function of the independent variables to the data. This equation can then be used to predict reliability for the component for which it was developed. It must be noted that the empirical approach provides no information concerning the details of failure. Indeed, one of the main advantages of this approach is that no theoretical relationships are needed. The identification of all pertinent independent variables is quite important, however, because if an independent variable affecting reliability is omitted, the resulting empirical correlation will be invalid since it does not account for the influence of the variable omitted.

The empirical approach is sometimes referred to as the "regression analysis" technique. This identification, while used quite extensively, is unfortunately not descriptive of the method. Regression analysis is simply a mathematical method of fitting an equation to a set of data points. Thus, regression analysis is merely a tool used in the empirical approach. The term empirical denotes relationships derived directly from experimental data rather than relationships derived from theoretical considerations.

The use of "K-factors" to modify reliability predictions for different operating and environmental conditions is an empirical technique in which each "K-factor" is used to account for the effect of an independent variable or a group of independent variables.

The Weibull (7) distribution, an empirical equation of the form

$$R = \exp \left[-\left(\frac{t - t_o}{\eta} \right)^{\beta} \right]$$

has been used extensively in empirical mechanical reliability prediction. The equation is fitted to a set of experimental data by determining the values of t_o, β and η that give the best fit in some sense. Fitting equations to data is discussed in the section on TECHNIQUES FOR ANALYZING DATA (Regression Analysis).

System Reliability Prediction. For a system composed of two or more components or sub-assemblies, reliability prediction techniques can also be classified as theoretical or empirical in nature.

1. Theoretical approach. The theoretical approach requires that some means be developed for predicting the reliability of the system assuming that the reliability of each of the components is known. The general approach requires that a "block diagram" of the system be constructed in which the components of the system are connected in series and parallel arrangements. The failure of any of several series-connected components will cause failure of the system. Parallel-connected components represent redundancies. In the simplest case, the reliability of a system of series-connected components is the product of the reliabilities of the components, providing the failure modes of the components are independent of one another. This concept has found wide application in the prediction of reliability for electrical and electronic systems. For most mechanical systems, failure modes of components are not independent. In addition, for a complex mechanical system, the block diagram may be quite complex.

There are three approaches to the prediction of system reliability based on a block diagram (2). These have been termed mathematical modeling, simulation (also termed Monte Carlo techniques), and the determination of limiting values (also called the Method of Bounds). The approach called

"mathematical modeling" has been widely used; therefore, the term "mathematical modeling" is widely used to designate the prediction of a system reliability based on the reliabilities of the components. In this method, equations are written to describe the relationships of the block diagram mathematically. In the simple example referred to earlier, the mathematical model is an equation in which the system reliability is the product of the component reliabilities. Bayes' probability theorem can be applied to complex systems and those in which the logic diagram cannot be constructed from only series and parallel connected components (8). Chou (9) describes the Bayesian approach as asking: "What is the probability of the hypothesis given the sample result?" On the other hand the classical approach asks: "What is the probability of the sample result given the hypothesis?"

For extremely complex systems, the formulation of the mathematical model may be either impractical or impossible. In this case, the simulation or Monte Carlo method can be used. The simulation method consists of selection of a random sample of each component reliability and combining these samples according to the block diagram to obtain a measure of the reliability of the system. The process is repeated a large number of times, utilizing a digital computer with a random number generator, so that a distribution of system reliability is obtained.

Prediction of system reliability using the Monte Carlo technique for a complex system requires very complex and difficult to write computer programs, thus, use of the Monte Carlo technique will require a high level of computer programmer-design engineer effort.

The Method of Bounds is simpler and less time-consuming than mathematical modeling or simulation. The Method of Bounds, as the name implies, is a procedure for determining an upper and lower limit between

which the true system reliability lies. The main advantage of using the Method of Bounds for a mechanical system is that component failures do not have to be independent, thus many mathematical complexities (or mathematical simplifications that reduce the accuracy of the mathematical model) encountered when using the "mathematical modeling" approach are avoided. The Method of Bounds approach seems to have the most promise for the prediction of system reliability in terms of component reliability.

It is obvious that the theoretical approach for prediction of system reliability is necessary in the design of many new systems. The key to the application of the theoretical approach lies in the requirement that component reliabilities must be known and known precisely. Prediction of component reliabilities has been discussed previously. The need for precision merits further discussion. If the reliability of a system is calculated from the reliabilities of the components, each of which contains some uncertainty, there will be uncertainty in the calculated value of system reliability due to the uncertainty in the component reliabilities. If the number of components is quite large, then the uncertainty in the system reliability value may be extremely large, even if the uncertainty in the component reliabilities is small.

Consider a system consisting of n series-connected components whose failures are independent of one another, so that the system reliability is the product of the n component reliabilities. In order to illustrate the point very simply, consider a case where the percentage uncertainties in the reliabilities of all components are equal and result from normally distributed error. In this case, the percentage uncertainty in the system reliability is $\sqrt{n}$ times the percentage uncertainty in the component reliability (10). For a relatively small system of 100 components, then, if the uncertainty in the component reliabilities is ±5%, the uncertainty

in the system reliability is ±50%. The uncertainty in the system reliability value is so large that the predicted system reliability value is useless.

In general, the larger the system, the more precise the component reliability values must be if the system reliability is to have an acceptably small uncertainty. There exists then, an upper limit on the complexity of a system for which precise prediction of system reliability is possible.

2. Empirical approach. In the empirical approach for prediction of the reliability of a system, the system is treated as a component and a mathematical relation based on experimental data for the reliability of the system as a whole is developed. The procedure is exactly the same as the procedure discussed for a component. The work of ARINC for compressors, turbines and pumps is an example of this approach (11). The empirical procedure avoids the requirement that the reliability of each component be known. Further, the often complex and imprecise procedure of theoretically predicting system reliability based on component reliability is unnecessary. The empirical method is desirable for many systems such as pumps, valves, compressors, etc. that are widely used as components of larger systems. The term "generic failure rate" is frequently applied to empirical failure rates determined for a particular system such as the centrifugal pump. "K-factors" are used to modify the generic failure rates for specific types of centrifugal pumps, different operating or environment conditions, etc.

Techniques for Obtaining Data

One of the greatest problems in mechanical reliability analysis is the prohibitive volume of data required to accurately establish quantitative working models for mechanical systems with any degree of complexity.

For example, if a mechanical device with 10 factors affecting reliability (and many mechanical components have many more than 10) is to be tested with 10 data points per run, and 3 runs for different levels of each factor, a total of more than a half million test runs (10×3^{10}) are necessary to completely isolate the effects of each factor. Of course, good engineering judgment permits omitting most of these test runs, but the greater the number of runs eliminated, the greater the possibility of overlooking a significant factor in the reliability.

Since mechanical components have many failure modes and many factors affecting each failure mode in some cases, one of the most important contributions that is needed in mechanical reliability is better techniques for obtaining data with special emphasis on getting more information from a smaller volume of data. Investigators in the fluid mechanics and heat transfer sciences have had remarkable success with the technique of combining variables into dimensionless ratios such as Reynolds number, Prandtl number, Nusselt number, etc. This technique reduces data requirements to a small fraction of what would otherwise be needed for the same amount of information. This technique should offer a real opportunity for improving the data requirement problem in mechanical reliability. It is discussed in more detail in the part of this report entitled FURTHER WORK NEEDED.

In any case, the production of data in a suitable manner is necessary for quantitative work in mechanical reliability. Many techniques are known and used for obtaining reliability data. These techniques are often divided into groups by some dividing method such as listed and briefly described below.

Scientific method vs. statistical method. One of the more general ways of describing the approach to obtaining reliability data is called

the scientific method vs. the statistical method. In the scientific method data is obtained to verify a hypothesis or some expected behavior which has been developed from theoretical or other knowledge. The data also serves to establish the numerical value of experimental constants to be used. In the statistical method data is obtained to establish a distribution of a parameter such as failure rate or possibly to find the distribution of a parameter in the scientific method already mentioned. That is, the statistical method may be used separately or in conjunction with the scientific method. In any case the statistical method associates some degree of certainty (or uncertainty) with the predictions to be made from the data.

Full Life vs. Accelerated Testing. Full life (or normal) testing implies testing until failure occurs in an idealized or actual operating condition that is as close as possible to the expected normal operating condition. This method of obtaining data can be quite expensive and time consuming, but it is generally recognized as the best method to use if the most accurate data is to be obtained. Accelerated testing refers to the technique in which the testing time scale is compressed by increasing the severity of the operating conditions. This technique is used to save time and cost, but usually at the expense of accuracy. Accelerated testing has proven to be of value in some cases such as when the number of cycles until fatigue failure occurs is the most important thing or in the cases where some data is needed as soon as possible to establish spare parts needs, but it has mostly failed when used as a technique for obtaining data for design improvements. The main problem with accelerated testing is accurately interpreting the results. That is, converting the compressed schedule data to normal schedule data with enough certainty to give useful results. Also accelerated testing often introduces new modes of failure

and extreme care must be used to avoid this problem when establishing the accelerated test.

Actual vs. Simulated Testing. (Field vs. Laboratory Testing). Simulated testing generates data under operating conditions which are artificially created. It may be full life or accelerated testing using the scientific or the statistical method but differs from actual operating conditions to the extent that the artificial conditions desired are produced. Wind tunnel testing is one of the better known methods for obtaining data from simulation tests. The saving in time and cost can be substantial. The main pitfalls in simulated testing are similar to the pitfalls of accelerated testing--accurate application of the data to the actual conditions and seeing that failure modes are not modified or new failure modes introduced.

Tests by Levels. One way of classifying the methods of obtaining data is by level. The word level doesn't always mean the same thing when applied to reliability, but the most commonly accepted meaning is with reference to level of function. That is, the level is lowest for parts (the smallest separatable pieces) which make up subassemblies (combinations of parts with no specified function). Subassemblies are combined to produce assemblies, which are combined to produce subsystems (which have specified functions) and subsystems are combined to produce systems which are the final product of interest. More abbreviated ways of using the level terminology include only components subsystems and systems in a similar manner as described above. In any case, some of the advantages of testing at high levels (systems or subsystems) are: (1) much less data is required to establish failure rates, (2) the results are more accurate when applied to the whole system, and (3) time and costs of data are reduced. Advantages of testing at lower levels (parts and

subassemblies) are: (1) more insight is obtained on how and why failure occurs, (2) more extensive tests may be made on critical components at less cost, and (3) tests may be designed to obtain data for a specific purpose (such as design improvement).

One important problem in using numerous low level tests in combination to produce data for predicting reliability of a complete system is the "error compounding" previously referred to. For this reason--and some others--test data usually cuts across the spectrum of levels in some form to compromise the advantages and disadvantages of complete testing at one level.

Destructive vs. Nondestructive Testing. Techniques for obtaining data are sometimes classified as destructive or nondestructive. In many cases there is no choice, the product is used once and no longer exists. A large number are tested and only the survivors have a possibility of being re-used. In other cases only parts or components of the system are destroyed by reliability testing and may be replaced so that the system test is essentially a nondestructive test. In other cases, such as wear tests, the degree of destruction may be selected with a useable product or component left for whatever purpose one might have. If a choice or selection is to be made within some given constraints, it is most likely to be made on a cost basis, although some other purpose such as a time delayed continuation test may be of interest to determine the effects of idle time or standby service.

General Data Programs vs. Special Testing. Many sources of data that are potential mechanical reliability data sources are already in existence. These include the Navy's Maintenance Data Collection System, Government Industry Data Exchange Program (GIDEP) and others. Since most of this data is not taken primarily for reliability analysis, a problem

exists in establishing all the needed information about the product of interest. This needed information might be additional descriptive data pertaining to the design, manufacture, or more likely the use of the product. Such data is more likely to be useful at the high levels (system or subsystem) of analysis with limited ability to use the data to establish why and how failures occurred and therefore improve design. Special tests are more apt to be needed to determine the design variables that affect reliability the most and in what way so that design improvements may be made. This may be summarized by saying that low level testing is essential for design improvements and special tests are more likely to be required since general data programs are not likely to have a format suitable for using the data in this manner.

Other Techniques and Terms Used in Obtaining Data. Peripheral testing is a technique for obtaining data which is mainly for the purpose of gaining more knowledge on how the product being tested is affected by certain changes in the operating conditions. Accelerated testing might be considered as a special case of peripheral testing in which the known modes of failure are purposely affected by the test. A true peripheral test would be used to determine whether or not a failure mode is affected by changing factors such as temperatures, humidity, etc. and is therefore much broader in concept than accelerated testing.

Service Life Evaluation and Surveillance Testing are two closely related techniques used to obtain data from a large number of items currently in service that normally fail in some gradual way over a period of time. In general these techniques involve the selection and analysis of a number of items to determine the rate and nature of approach to failure for the purpose of estimating the remaining service life. Surveillance testing implies a regular interval selection for current time status

of deterioration, whereas Service Life Testing is a more thorough analysis aimed at estimating the remaining service life.

Truncated (or Censored Life) testing is a technique for obtaining data in which abbreviated tests are designed for the purpose of giving data which may be used to extrapolate the needed information. Such tests do not necessarily, and usually are not, cases of accelerated testing.

Sequential testing is a technique closely related to truncated testing, except in sequential testing the length of test is not decided before testing starts. After each sequence of tests, a decision is made as to whether further testing is needed to provide the needed information.

Degradation tests, step stress tests, and derating factors are special techniques associated with accelerated testing and commonly used in electronic component testing but not commonly used in mechanical reliability. Degradation testing is a technique used to obtain data for determining how an important characteristic of a part drifts or changes with time or use so that it affects the reliability of the component. Step-stress tests are tests in which an operating variable is increased in severity in steps so that a definite observation may be made to establish the quantitative relationship between the operating variable and some failure mode or mechanism. Derating factors are numbers used to relate a quantitative measure of the operating variable to a standard value of the variable. The derating factor then becomes an indicator of how much a reliability figure of merit is affected by the different values of the operating variable.

Diagnostic Monitoring is a technique used mainly to detect failure modes but is included here since data is obtained first and this data used to establish failure modes and mechanisms. The technique consists of monitoring measureable values (temperature, pressure, vibration, etc.) on

the item while in use and using the values with their source point to acquire knowledge about failure, wear, etc.

Statistical Monitoring (12) is a data technique developed by Oklahoma State University in work for the U. S. Army. It might be called a special type of diagnostic monitoring or a complement to it, with emphasis on methods for using the data.

Functional Reliability Evaluation Technique (FRET) (13) is a technique developed by IBM Corporation. It might be simply described as the application of a combination of accelerated testing and sequential testing to components that have specific functions which lend themselves to the method. It was used mainly on printers, card readers, optical readers, punches, etc. and can probably be used on similar devices. Its adaptability to a wider range of items would present some problems.

In closing this portion of this report on Techniques for Obtaining Data, it is obvious that a large number of techniques have been devised and used to obtain data in reliability studies. Some techniques have very obvious limitations and disadvantages as well as some obvious advantages, but in the process of selecting the technique to use in obtaining data the main factors to consider will usually be time, cost and possibly personnel. Working within the constraints of these factors it then becomes important to answer several questions such as: What is the purpose of the data? (identify failure modes; confirm a theory; develop a model; improve design; locate a factor; etc.) What is the minimum amount of data needed? What is the best format in which to generate the data? Are special tests necessary or needed, or will existing data sources provide the needed answer? Other questions must also be answered before or during a data selection procedure. This topic is discussed in other further sections of this report.

Techniques for Analyzing Data (Regression Analysis)

When experimental data is gathered, the purpose is usually to establish a relationship between a dependent variable and one or more independent variables. We want to be able to estimate the value of the dependent variable from values of the independent variables. We usually want the relationship between the variables in the form of an equation. For example, suppose we have a set of (x, y) values and want to determine a relationship between y and x in the form of an equation.

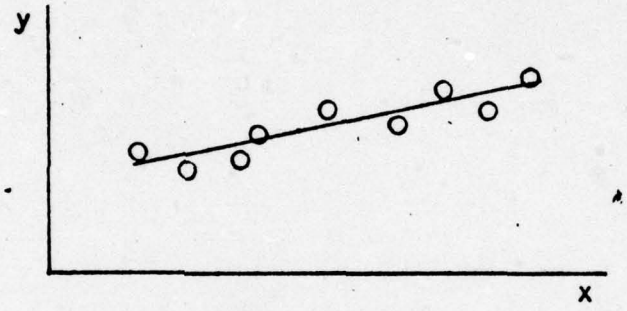

Figure 1.

We may plot the data points as shown in Figure 1 and draw a smooth curve that approximates the data. For the set of data in Figure 1, a straight line is a good approximation of the data. The equation we seek would be the equation of a straignt line having the form

$$y = a + bx$$

where a and b are constants. The general problem of finding the equations of curves which approximately fit given sets of experimental data is called curve fitting. Curve fitting, of course, provides an equation from which the dependent variable can be estimated from values of the independent variables. Regression is referred to as this process of estimating the dependent variable from the independent variables. The mathematical procedures of determining the equation of the curve which best

approximates the data is called regression analysis. In the above example, we would say that regression analysis could be used to determine the values of a and b which makes the equation $y = a + bx$ fit the data best in some sense. The "best fit" is usually defined as the equation for which the sum of the squares of the deviations of the values of the dependent variable predicted by the estimating equation from the data point values of the dependent variable is a minimum. This is usually termed the "best fit in the least squares sense." Curve fitting based on the "lease squares" definition of best fit is often called "the method of least squares" or "least squares curve fitting."

The equation of the above example is a simple, linear regression equation. The designation simple refers to the fact that only one independent variable is involved. If more than one independent variable is involved, the regression is called a multiple regression. Because the data of the above example could be approximated satisfactorily by a straight line, the regression is termed linear. If the data cannot be satisfactorily represented by a straight line, the regression is referred to as a non-linear regression.

Polynomial equations or variable transformations are frequently employed for non-linear regression. The variable transformation allows the use of linear regression techniques to develop non-linear approximating equations. For example, if a set of (x, y) data falls along a straight line when plotted on logarithmic coordinates, then by transforming the variables x and y to log (x) and log (y), respectively, a linear equation of the form

$$\log (y) = \log (a) + b \log (x)$$

can be determined which fits the data. The equation can also be written in the form

$$y = ax^b$$

which is clearly non-linear.

It will be noted that a regression equation is an approximation to the set of data. In general, if the regression equation is plotted along with the data points, the equation curve will not pass through all the data points. Correlation Analysis deals with the accuracy of the regression, or how close the regression curve comes to passing through each data point.

The numerical calculations required for regression analysis are usually performed utilizing a digital computer. Generalized computer programs for regression analysis are available. Regression analysis necessary to determine empirical reliability predicting equations from experimental data is clearly within current state-of-the art capabilities.

Other Techniques Used in Mechanical Reliability

Fault tree analysis is a technique using an event logic diagram rather than a block diagram to analyze system failures. Although fault trees may be used in reliability analysis they have traditionally been used to analyze safety (loss of life or rare event) hazards. Eagle (14) describes reliability analysis as "hardware" oriented and fault tree analysis as "event" oriented. Points in favor of fault tree analysis include: (1) graphical format provides additional ability to convey information, (2) multiple or dependent failure modes are easier to handle, (3) non-hardware items such as human factors are easier to handle, and (4) more depth to the analysis is provided. Disadvantages include: (1) more time and effort is required to prepare it, (2) the information is not as compact as equations, (3) and broader scope is sacrificed for more depth.

Electric Circuit Analogs is a technique developed and briefly investigated by ARINC Research Corporation. Although it has not been developed enough for a complete evaluation, it seems that there are too many relationships in mechanical reliability that are not well enough understood at the present time to model in any form for electric circuit analogs to have widespread application.

Operator Judgement Versus Measured Performance Characteristics (Weighting Functions) is another technique developed by ARINC Research Corporation. The method is theoretically sound but like many other theories, application is extremely difficult because accurate quantitative input for a real situation is possible for only the simplest problems--where other methods also give good results.

Tabular System Reliability Analysis (TASRA) is a technique developed by Battelle Memorial Institute for the Air Force Flight Dynamics Laboratory (15). TASRA is an attempt to combine the good characteristics of Fault tree analysis with other procedures used in reliability to make sound reliability predictions at the design stage. The method seems to have merit for electronic circuits and some mechanical systems that have reliability characteristics similar to electronic circuits. When TASRA is applied to the more complex mechanical systems, however, there are many questions and few answers--like many other techniques.

RECOMMENDED APPROACH

Any general approach to the prediction of mechanical reliability must include the capability of:

1. predicting reliability of single components
2. predicting reliability of an assembly of components (system), either (a) without reference to component reliabilities (treating the assembly as a single component), or (b) based on the component reliabilities.

At the present time no unified theory for mechanical reliability prediction of components exists. Although the stress-strength-time theory can be applied to single load-bearing parts, much supporting information concerning load distribution as a function of time, wear rates, and statistical distribution of material properties as a function of time (due to fatigue, corrosion, etc.) is required. This information is not now available for the many complex geometries and numerous operating conditions of the multitude of different components that must be covered in a mechanical reliability handbook. Most of this information must be determined experimentally using large sample sizes. In addition, application of the stress-strength-time theory has not been demonstrated for non-load-bearing components.

It appears that in most cases, the empirical approach to component reliability prediction is the desirable approach. Further work should be done to identify the cases in which the stress-strength-time theory can be applied. The major obstacle to the implementation of the empirical approach to component reliability prediction is the tremendous amount of experimental data that must be acquired. Further study aimed at reducing the quantity of experimental data required is needed as the next step in

predicting component reliability empirically. Some possible approaches are described in the section on FURTHER WORK NEEDED.

The reliability of some commonly used systems such as pumps, valves, compressors, etc., can be predicted empirically in the same way that the reliability of single components can be predicted. For systems of a new or unique design, however, the system reliability must be predicted from the reliabilities of the components. For complex systems, this is a difficult task. As has been noted previously, the uncertainty in a value of system reliability predicted from component reliabilities using a block diagram is often so large that the reliability value is useless. This difficulty will be alleviated somewhat as component reliabilities with lower uncertainties become available. Precise prediction of system reliability from component reliability will never be feasible for systems consisting of a large number of components.

At this time, there is no alternate means of satisfactorily predicting the reliability of a system consisting of a large number of components from the component reliabilities, unless the uncertainties in the component reliabilities are extremely low. Effort should be directed toward developing such a method.

FURTHER WORK NEEDED

Further work needed can be divided into four main headings. They are: (1) Investigation of ways to reduce the volume of data required, (2) Investigation of several special subjects that affect any unified theory or approach to mechanical reliability, (3) A more detailed analysis of the recommended approach described in the previous section, and (4) A more detailed analysis of the factors affecting the format needed for a mechanical reliability guide in design. Each of these topics is discussed more fully in the following paragraphs.

Ways to Reduce the Volume of Data Required

As stated in other parts of this report, one of the main problems in mechanical reliability analysis is the data requirements. Several techniques with some potential for helping in this area are discussed in the following paragraphs, but all the methods do not have the same potential.

Using Dimensionless Ratios. The method that probably has the greatest potential in reducing overall data requirements is the use of dimensionless ratios of variables. This technique has been used extensively in fluid mechanics and heat transfer to reduce data requirements to a small fraction of what they otherwise would be. Lockheed Aircraft put a limited effort on this technique as a small part of an investigation for the Bureau of Naval Weapons (16). The investigation was limited to solenoid operated hydraulic valves used in aircraft and the results were not sufficient to draw any conclusions on this technique as a whole. It is the opinion of the authors of this report that other types of mechanical equipment might be more suitable for this technique. A prime prospect is the class of mechanical equipment that transmits power by rotation and

fails mostly due to wear. Examples are splines, gears, cams, sprockets, and possibly bearings, seals, impellers, pulleys, belts, chains, cable, conveyors, rollers, tires, and casters.

For this type of equipment--rotating power transmission equipment that fails mainly by wear--an attempt would be made to establish one or more dimensionless ratios of such parameters as horsepower transmitted, torque, tooth pressure, speed or rpm, tooth (or other) dimensions, material hardness, diameter, and the like so that the overall behavior is dependent upon the combination of values (just as fluid flow behavior is dependent upon Reynolds number). The dependent variable would be a dimensionless wear value (actual wear in inches divided by some special dimension such as tooth depth) so that the value would be meaningful for any similar application. Such an approach would permit a family of curves plotted with the curves progressing from one class or geometry extreme to another. For example, the family of curves might extend from long slender splines to short stubby splines or from thin large diameter gears to wide small diameter gears and similar variations for other hardware items.

A slightly different way of using dimensionless ratios is in the form of factors. This method would consist of constructing curves of factors to be used with wear rates (or other figures of merit) vs. dimensionless ratios of parameters such as hardness or misalignment. The curves would be such that when a material hardness equal to the referenace hardness is used the factor would be 1.0; also a factor of 1.0 would be obtained from a curve when some average (or reference) value of misalingment is used.

Although this method of using dimensionless ratios has much potential if successfully developed, it is also true that the probability of

successfully developing the method is lower than that for the other methods described in the following paragraphs.

Designing Test Procedures. Another method of reducing data requirements to some degree is that of developing procedures to design tests for maximum use of data. A large number of considerations should be made before designing a test and obtaining data for reliability studies. The procedures developed should insure that the data from the tests are useful for the purposes intended. For example, a series of tests intended to provide data for improvements in design should have variables controlled by the designer as variables in the test. If a designer is to use data for the selection of the most reliable type of component to fit his needs, then data must be available which relates the different types suitable to reliability. In fact if design improvement is the sole purpose of the data, nothing is gained at all by getting data which relate operation, installation, or manufacturing variables to reliability unless these variables are indirectly affected by the designer. This method does not offer the potential for results that the method of dimensionless ratios does, but a definite contribution could be made by developing procedures to be used in this method.

Using Existing Sources More Efficiently. A third way data volume needs can be reduced is by finding ways of using existing data more efficiently. Existing general data programs such as the Navy's Maintenance Data Collection System and GIDEP are valuable sources of data for mechanical reliability analysis. Data from such programs could be made more useful by establishing standardized or reference formats for reliability information so that all needed factors (such as design variables) are included in some coded manner with the data. The

procedures developed here would no doubt be influenced by the topic of equipment classifications discussed in this section of this report.

Special Subjects to be Investigated

As a part of further work needed, several topics need special attention to determine ways of organizing, classifying, or in some way evaluating their place in any overall or unified theory on mechanical reliability as it relates to design. Three of the more important subjects to be discussed in more detail are (1) figures of merit (dependent variables), (2) mechanical equipment classification, and (3) failure modes and mechanisms.

Figures of Merit. Figure of merit is the name given to the dependent variable which indicates reliability quantitatively. Some of the more common ones used are: (a) Mean time between failures (MTBF), (b) Failure rate, which is usually the inverse of the mean time between failures, although several modifications of the definition of failure rate are used, (c) Time to failure (TTF), (d) Stress to failure (STF), (e) Mean time between maintenance (MTBM), (f) Mean time between corrective maintenance (MTBCM), (g) Mean time between preventive maintenance (MTBPM), (h) Mean time between replacements (MTBR), (i) Mean time to repair (MTTR), (j) Mean down time (MDT), and several others which include mean or reference values of maintenance man-hours to repair; parts or labor costs to repair, and other costs or time bases of reference. Each of these dependent variables has its good and bad features. Some are better for providing the needed information than others, but any unified approach should include procedures for selecting the best figure of merit to use for a given set of conditions. Since the best selection would depend partially upon the type of equipment and expected failure

modes, the study of this topic would also include some consideration of all these topics.

Mechanical Equipment Classification. Mechanical hardware exists in such a wide range of functions, types, and sizes that any unified approach to mechanical reliability is dependent to some extent on how this subject is treated. Since one might be interested in considering the mechanical reliability of a simple component such as a bearing or seal, or a much more complex system such as a complete refrigeration system, an orderly form of classifying or organizing this subject should be considered from several viewpoints. Since the problem is complex due to the many factors involved, a large number of ways naturally exist for classifying the subject. The RADC Nonelectronic Notebook (17) contains failure rate data on more than 300 mechanical part classes and subclasses and this listing is by no means complete for mechanical equipment. Some mechanical reliability studies group equipment into three categories: components; subsystems; and systems. Others use five categories: parts (components); subassemblies; assemblies; subsystems; and systems. These designations have some value when properly defined, but some type of additional grouping is needed based on similarities related to mechanical reliability. Groupings and subgroupings might be based on the most suitable figure of merit; mode of mechanism of failure; or cause of failure. For example, items might be included in a class or subclass that have a high failure rate due to difficulties in manufacturing procedures. One class or subclass might be components that fail mainly due to wear--or specific types of wear. Combinations of the above factors could be used to form classes or groups. An example might be items that mainly fail due to fatigue and use a number of load cycles as a figure of merit. Some effort should be put into this area of

study before completely formulating a unified approach to mechanical reliability.

Failure Modes and Mechanisms. Various definitions exist for the terms of "failure mode" and "failure mechanism". Mode of failure usually means the manner in which failure occurs. More common ways include fracture, fatigue, wear, corrosion, creep, deformation and the like for simple component type items. The term, "failure mechanism" usually means the physical or chemical process or agent involved in the failure. Usually the mode of failure is important to the designer whether or not the mechanism is. Several generalized approaches to failure have been developed and used. One of the most common and general is that any mechanical component has an inherent or generic failure rate which is modified by the conditions under which the component is used. Most generic failure rates are considered to be constant with time. When this simple approach is used the familiar exponential curve of reliability is obtained. Most components have more complicated curves, however, due to infant mortality in early life and high failure rates at later times due to wear, age, corrosion, or other time dependent factors.

One of the more complete studies of this subject was made by Mechanical Technology Incorporated for the Office of Naval Research (18). In this study failures are divided into three categories, (1) very slow deterioration, (2) relatively rapid deterioration, and (3) sudden catastrophic failure. In addition, failure modes and malfunctions were classified into component, subsystem, and system failures, with subclasses under each one of these. Component failures, for example, were subclassified as mechanical (fracture, rupture, creep, etc.), hydraulic (leakage, pressure loss, etc.), thermal (oxidation, thermal cracking,

distortion, etc.) and electrical (signal loss, power interruption, etc.). Useful descriptive information is contained on many of the modes and mechanisms that should be of value to anyone investigating this subject.

Another point of view in the "how and why" of failure has to do with how failure is related to the design, manufacture, use, or installation of the component being considered. All this, plus the complicating factors of environment and effects of time make this one of the more complex subjects related to mechanical reliability. A considerable effort in this area is necessary before completing a unified approach to the subject of mechanical reliability as it relates to design.

Further Analysis of the Recommended Approach

The recommended approach described in a previous section of this report is based on preliminary studies and should be investigated more fully. Further data studies as well as further studies in other subjects described earlier in this section of the report should be used as necessary to modify the recommended approach mainly to make the procedure more specific.

Some ideas to be explored include a check list of actions by the designer to be used in selecting the basic method to use. Such a check list would include constraints to be considered (time, money, personnel, etc.) and questions to be considered relating to purpose and importance of the design as well as other factors important in establishing the basic method to use.

Once the basic method is established, procedures are then needed for several additional steps such as the selection of the dependent variable (figure of merit), determination of the equipment classification or grouping; establishing the expected modes and mechanicms of failure;

and to what extent reliability is dependent upon manufacture, use, shipping, storage, and installation as well as design.

After the designer has followed procedures discussed above he should be directed by specific guides in obtaining data from existing sources or in establishing suitable tests for use in determining quantitative values of mechanical reliability. If data sources are already available, guides to their use should be provided. If new tests are necessary, guides for developing such tests should be provided. Additional information should be helpful in determining if some combination of existing data with new tests is a better procedure to follow.

Finally, a recommended approach to mechanical reliability should be thoroughly evaluated and illustrated by a variety of examples that are as realistic as possible which provide an opportunity to pinpoint weak as well as strong points, and especially the limitations on its use before it is implemented.

Mechanical Reliability Design Guide

A mechanical reliability design guide is the logical result of an organized approach to implementing a unified theory of mechanical reliability as it relates to design. After the procedures described in the preceding section have been established, illustrated, and evaluated, they should be included in such a guide along with appropriate additional information.

Establishing the content and format of a mechanical reliability design guide is a major task within itself and the total effort necessary is dependent upon some preliminary efforts at establishing primary and secondary goals and to some extent the range and scope of such a guide.

Such a guide must be a compromise on generality and detail so that it is broad enough for use in most cases and detailed enough to give

useful results without being too unwieldy. A compromise on simplicity vs. complexity is necessary to encourage its use on the basis of simplicity yet provide meaningful results on the more complex applications.

Decisions must be made on the amount (if any) and the format of information on such topics as definitions and terminology, techniques, independent variables, failure modes, equipment classifications, data sources, and testing procedures. The purpose, scope, and limitations of the guide should be clearly stated as well as procedures for using in as brief and concise form as possible.

One of the most important parts of this effort is the selection of the format to use. The format must be suitable for continuous additions and revisions so that new concepts and information may be added without major changes. The format must also be designed to accept data from the most common existing sources (such as the Navy's MDCS) as well as having enough flexibility to accept data and information from a wide range of additional sources.

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